Physics of Airborne EM Systems

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SUMMARY

We investigate the basic physics of electromagnetic exploration with the aid of a simple model that consists of a thin tabular target in a conductive host. The variables are host conductivity, system dimensions, and frequency of operation. We measure the system effectiveness by using the ratio of the target response to the host response. In terms of this quantity we find that there is an optimum target detection window ,both in frequency and in time, whose position is defined by the target parameters. Within this window, the amplitude of the target signal is controlled by the host conductivity and by the system dimensions. For all system configurations considered, the ratio of target to host response is maximized for the smallest separation of transmitter and receiver. For the simple model used here a short , 1m, separation transient co-axial system flown at a height of 30m over a 50m deep target in a 10 mS/m half space has a detection ratio that is about five times that of a 30m long frequency domain machine.

INTRODUCTION

Airborne electromagnetic (AEM) systems were first developed in Canada and Scandinavia to find electrically conductive sulfide ore deposits. The overburden consisted of tens of meters of resistive glacial till and the host rocks were usually resistive. Consequently a conductive body in the form of a rectangular sheet in free space was a useful laboratory or numerical model for understanding the induction process, designing AEM surveys and interpreting the results.

The search for conductive targets in electrically conductive terranes however, involves different design criteria than those used in resistive areas. Now the response from the host rock becomes significant, if not overwhelming, and the variations or inhomogeneities in the host rock yield secondary fields which are difficult to distinguish from the desired targets. At this point the designers of AEM systems have the choice of developing a broad band system which can be used to map the conductivity in the subsurface or to develop a system which is optimized for the detection of the target whilst minimizing the response from the overburden and host rock.

In this paper we address the question of maximizing target response by investigating the basic physics of the electromagnetic response for a simple finite sheet in a conducting host. The goal is to present some guidelines for understanding and designing an AEM system that is optimized for detecting a deeply buried massive conductor in conductive terranes. The bulk of our study relates to a generic rigid boom coaxial system. We examine the effect of frequency, coil separation and host conductivity on the detectability of the target. Effectiveness of target detection is defined by the ratio of the target response to the host signal . An identical performance criterion can be used to assess time domain, step response data where the time of signal observation becomes a system parameter.

THE FINITE SHEET TARGET

The factors that control the response of a conductive target in a conductive medium can be examined with the aid of the simple sheet model of Figure 1 for the system geometry illustrated there. The target is 300m in strike extent, 100m in vertical extent and is characterized by its conductance (conductivity thickness product) of 100 S. It is buried 50 meters below the surface. The host half space is of uniform conductivity that ranges from 0.1 mS/m to 100 mS/m. Our idealized AEM system is shown schematically directly above the model at 30m terrain clearance . It can be configured as a vertical loop ,coaxial system (T_X - R_X), or a horizontal loop coplanar system (T_Z -R_Z). We have not examined results for the crossed coil (T_Z -R_X) configuration. For each case, the flight path height has been fixed at 30m above the surface or 80m above the target. The variables considered are the conductivity of the background medium, the transmitter-receiver separation L and the frequency of operation . In the time domain, we consider the magnetic field (H) response to a step transition in the transmitter current. For the analysis we use program EMIDSHEETS (available on demand from senior author) to compute (H_H), the magnetic field caused by currents induced in the host alone , the secondary fields from the target , (H_S) ,and the total field which is the sum of the primary field, the host field, H_H, and the secondary field H_S. The real and quadrature components or amplitude of these fields can be expressed in A- m per unit moment or in ppm of the primary field at the receiver . Alternately, the transient response for the host, the target or total fields can be calculated for a unit step change in the transmitter moment.

The detection effectiveness of any given AEM system configuration for the conductive target is defined by the ratio of the secondary field from the target, H_S ,to the field of the host H_H. We know that in reality the host will be inhomogenous and its response will be variable. If the detection ratio H_S/H_H for a simple homogenous half space is low, say unity, then it is unlikely that the target will be seen - the background variation is likely be on the same order of magnitude as the target response. Detection probability increases with increasing H_S/H_H ratio and becomes a certainty when this ratio exceeds three. Regardless of the absolute merits of this criterion for a specific system, and the H_S/H_H ratio for which detection becomes possible, it is an objective means of comparing different systems over the same target.

In addition to contributing to the measured fields , the presence of the conducting host alters the response of the target. Fundamentally ,the presence of the half space attenuates and shifts the phase of the fields reaching the target and returning to the receiver. Furthermore ,the induction of currents in the target is supplemented by the channeling of currents from the half space into the conductor. The latter , referred to as galvanic currents to distinguish them from the induction or vortex current caused by the changing magnetic field at the target, are of course not present if the target is in free space.

MODEL RESPONSE ANALYSIS

Frequency Domain

First, let us look at the quadrature component of the secondary and layer fields for a 10 mS/m host and a 30m coil separation with the system centered over the target. These data are shown in Figure 2(a) along with the quadrature target signal when the host is highly resistive. We see that the target signal is enhanced by current channeling in the conductive environment. It exceeds the host rock contribution by a factor of about two for frequencies below 100Hz. The corresponding data for the real component of the observable fields are shown in Figure 2(b). Most noticeable is the degree to which the target signal dominates the host rock response at all frequencies below 1000Hz.In that range, the detection ratio is just under ten. The target response below 100Hz is unaffected by the conductive host but we see substantial signal enhancement in the neighbourhood of 1kHz.

As others have observed in field data, we also note that the detection ratio for the real component is much larger than that for the quadrature component. Examination of other model data shows that this effect is independent of host conductivity or coil spacing. Even with the enhancement of channeling, the half space response overwhelms the target response above its quadrature peak. A more conductive body would be best detected at lower frequencies. Deepening the body will of course reduce the detection ratio but does not have much effect on the frequency at which it has a maximum . It appears then that for elevated dipole sources current channeling is not an important factor in determining the maximum H_S/H_H ratio.

When we examine the role of the coil separation L on the detection ratio for the real component of the observed fields, we find that for a conductivity of 10 mS/m the peak ratio occurs at a frequency of about 100 Hz and increases from a value of about 2 at L = 100m to a value of about 8 at L =1m. For a 1 mS/m half space, the detection ratio increases from around 32 for a 100m coil separation to nearly 300 when L is less than 10m . In a relatively resistive terrane the detection ratio falls off by an order of magnitude as we go from L=10m to L= 100m. However ,when the host conductivity rises to 10 mS/m the coil separation effect is reduced by a factor of about three. The peak detection ratio appears to be largely independent of host conductivity. For this target it occurs somewhat above 50 Hz where the induction number is about unity.

Time Domain

Typical step response transients for the 1m coaxial configuration and host conductivities of 10 and 0.1mS/m as well as the 10 mS/m host response are shown in Figure 3. Here we note the well known "window" effect where the target signal dominates the background only during a part of the observation time. The target can be best detected at about 2ms after the primary field extinction in a wide time window . Current channeling enhances the response at early time. The maximum detection ratio of about 10 is seen at 2ms at the smallest coil spacing. Let us now recall that he maximum H_S/H_H ratio for the 10 mS/m half space in the frequency domain was about 7.4 at an L value of 1.0 m. In the time domain this ratio is about 11.0 so it appears that ,in this case the time domain detection ratio at close separation is some 50% higher. The target visibility is severely lowered as the host conductivity is increased so that ,as in the frequency domain case, the target is barely visible in a 100 mS/m host . When the host conductivity falls to one mS/m the detection ratio rises dramatically to about 300 while the optimal time for signal observation is hardly changed.

CONCLUSIONS

Because of the simplicity of our test model ,this paper is mostly a demonstration of an approach that can be taken toward AEM system design. Nonetheless our study of AEM system parameters that control the response of a conductive target in a conductive environment leads us to make a number of practical observations. Turning first to the frequency domain let us note that there is an optimal frequency range for target detection. This factor only depends on the target properties and the optimal detection range is centered at the point where the target induction parameter is about unity, For our model this occurs at about 70 Hz. The amplitude of the detection ratio is influenced mainly by the host conductivity and to a lesser extent by the system dimensions. As is well known ,any system geometry can be used detect targets in a resistive environment but in regions where the host rock is conductive small scale systems appear to outperform those based on a large coil separation. Our findings for time domain systems are analogous to those reported for the frequency domain apparatus. Here we consider system step response as a function of time of observation rather than as a function of frequency. Our target conductor has a time constant of about 1.5 ms and so , as might be expected, the optimal target response occurs at about 2 ms after primary field extinction. Again, we find that the position of the target detection window is defined by the target time constant alone. Within that window the detection ratio is controlled mostly by the host conductivity but also to some extent by the system scale.

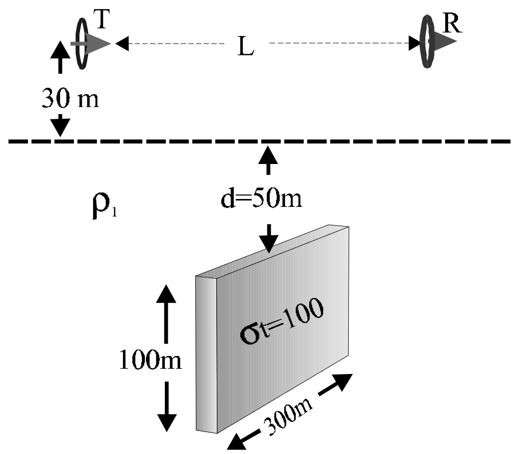
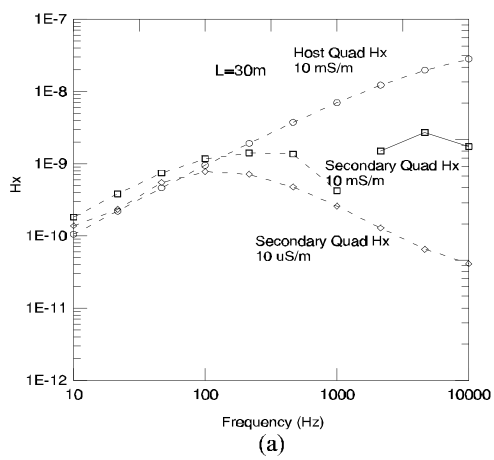


Figure 1. AEM system configurations and target model.



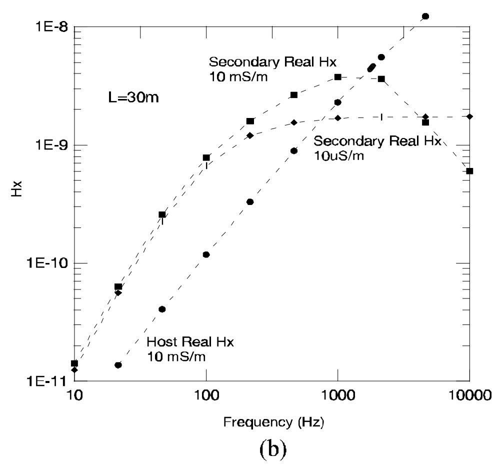


Figure 2. Secondary (a) quadrature and (b) in-phase magnetic fields for a 10 mS/m host conductivity and 30 m coil spacing.

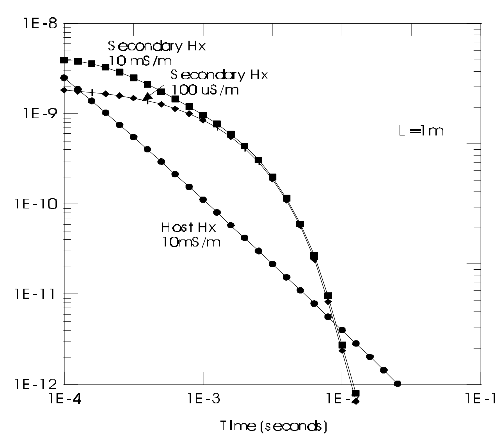


Figure 3. Secondary field transients for 1 m coil spacing and variable host rock conductivity.